A HUMAN BODY POSTURE SENSOR FOR MONITORING AND DIAGNOSING MSD RISK FACTORS

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ABSTRACT

Musculoskeletal disorders (MSDs) threaten the wellbeing and livelihood of a large number of construction workers incurring a significant cost to society. We present a new method to monitor and diagnose MSD risks in the workplace. The sensing unit of the system is an optical encoder encompassed within a non-intrusive exoskeleton to measure the joint angle of interest. This sensor can be applied to ball-and-socket and hinge-type joints of the human body, such as the shoulder, elbow, and knee joints. The system is contactless and does not require markers or cameras. Angle measurements are acquired directly without mathematical post-processing, thereby avoiding numerical noise and drift challenges. The system is a simple, robust, and deployable, but it currently lacks resolution of parallel degrees of freedom.

KEYWORDS

Motion tracking, Human joints, Angle measurement, MSD, Robotics, Gerontology

INTRODUCTION

Musculoskeletal disorders pose a threat to workers health and wellbeing throughout the course of their work-life and after retirement. In addition, these injuries impose tremendous direct and indirect costs on industry and the healthcare system as they try to cope with their long-term impact.

In a general sense, musculoskeletal disorders are present across the population. The risk factors leading to MSDs are biomechanically similar across the population in the sense that postures, force and time spent by different occupations lead to the injury (Kumar, 2001). The distinction is that people in certain occupations or lifestyles are at more risk of developing MSDs than others who do not share these same occupations or lifestyles. MSDs are chronic injuries; they can take a long-time to develop but when they develop, recovery is almost never complete.

The nature of MSDs and the way they develop make it important for researchers to understand how to prevent them. However, since everyday lifestyle involves exposure to their risk factors, complete prevention is impossible. On the other hand, decreasing the frequency of incidence is a desirable and achievable goal. Epidemiological, biomechanical, and ergonomical studies investigate MSDs to determine their sources, risk factors, and ways to decrease their prevalence through workplace redesign or new ways to perform everyday activities, such as carrying heavy loads and sitting in a chair.

When a person develops an MSD his/her lifestyle changes, and sociological effects often accompany this change depending on the type of MSD. For instance, low-back pain can prevent a person from carrying his/her baby or performing simple tasks that involves bending. Gatchel et al. highlight the fact that low-back pain is a psycho-socio-economic phenomenon and that physical factors are not the only contributor to pain (Gatchel, Polatin, & Kinney, 1995).

What makes MSDs more complicated is that there is no cure for many of them. Once a person develops it, the treatment is often through changing their lifestyle and the way the person performs everyday tasks. Without ergonomic redesign of worksites and tasks, a cure or a drop in the prevalence of MSDs is not achievable. Another complication of MSDs is inter-variability between people. While certain tasks are not harmful to some people, they can be very harmful to others. Keeping this in mind when designing an ergonomically safe environment complicates the process. The balance between health and productivity implies that tasks/workplaces should be designed to make them safe for everybody as well as maximize production. These criteria cannot be applied without casualties. Since a compromise will be established to include population within a predefined probability range around an average, there will always be individuals outside that range who will be subject to risk factors when they perform the work/task. Therefore, ergonomic redesign should not be the only tool to protect against MSDs. Even with ergonomic design, there is a need for ongoing monitoring to protect the population outside the assumed probability range.

Recent statistics on MSDs

To assess the size of the MSD problem, we discuss here injury statistics accumulated by Statistics Canada and the U.S. Bureau of Labor Statistics. According to (Statistics Canada, 2011), the average absence for the building and other support services was 8.6 days long in 2011. Figure 1 shows the average absence length in the same category for the last 11 years. The chart shows an ascending trend from 6.6 days out of work in 2001 to a peak of 9.1 in 2006. Henceforth, absence length stabilizes around 8.5 days which is 2 days longer than the average absence in 2001. Several scenarios could underlie this trend: a large intake of inexperienced workers joining the workforce recently without the proper training to avoid injuries, a change in construction technology leading to more severe injuries, or an aging workforce requiring more time to recover. Regardless of the exact underlying causes, the data indicate that workers are under heightened risk of developing severe injuries in the construction sector now as opposed to 11 years ago.

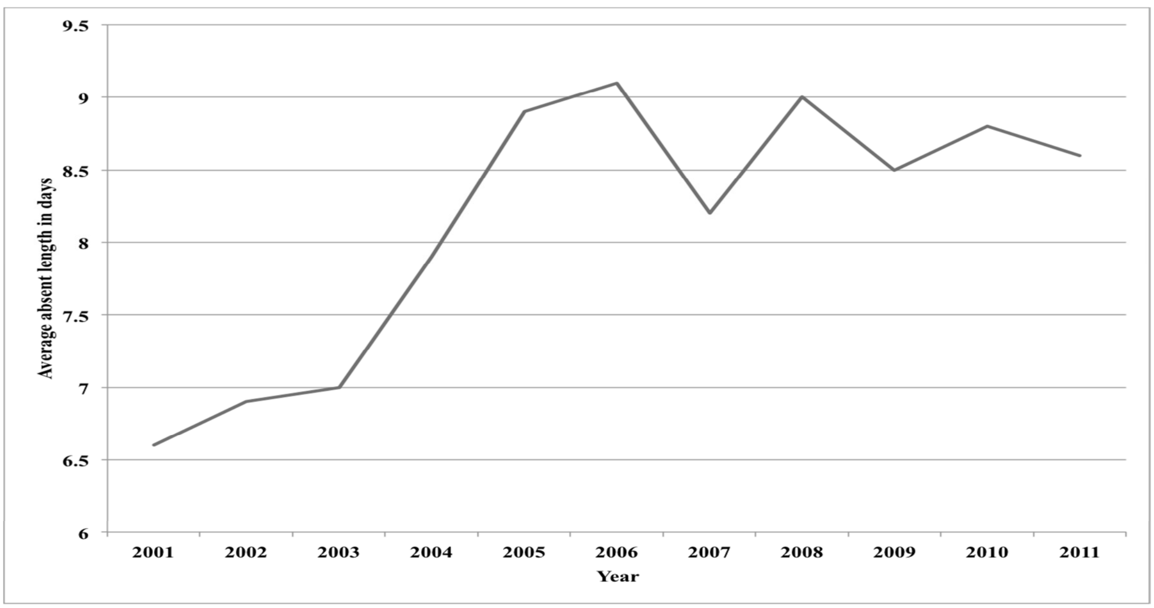

Figure 1- Absence rates in building and other services (Statistics Canada, 2011)

The trend is the same in the U.S; the number of injured workers is on the rise. Tabulated data on absence rates grouped by the type of work and injured body part indicate heightened risk of MSDs. According to (Bureau of Labor Statistics U S Department of Labor, 2012), the average time required for recovery from a shoulder injury is one month.

MSDs are present among all occupations because of the nature of the injury and the availability of its risk factors in all work environments. However, the degree of exposure to these risk factors is behind the increase in one type of occupation over others. In figure 2 the distribution of MSDs based on the job category is shown. Notice that construction labourers have a median of 12 days out of work, which is ranked second after the truck driver category that might suffer MSDs as a result of their commute on the roads. Also, nursing assistants and registered nurses require half as much time compared to construction laborers, however, nurses in general have more risk of having an injury. Thus, the typical injury is more severe among construction laborers but more common among nursing staff.

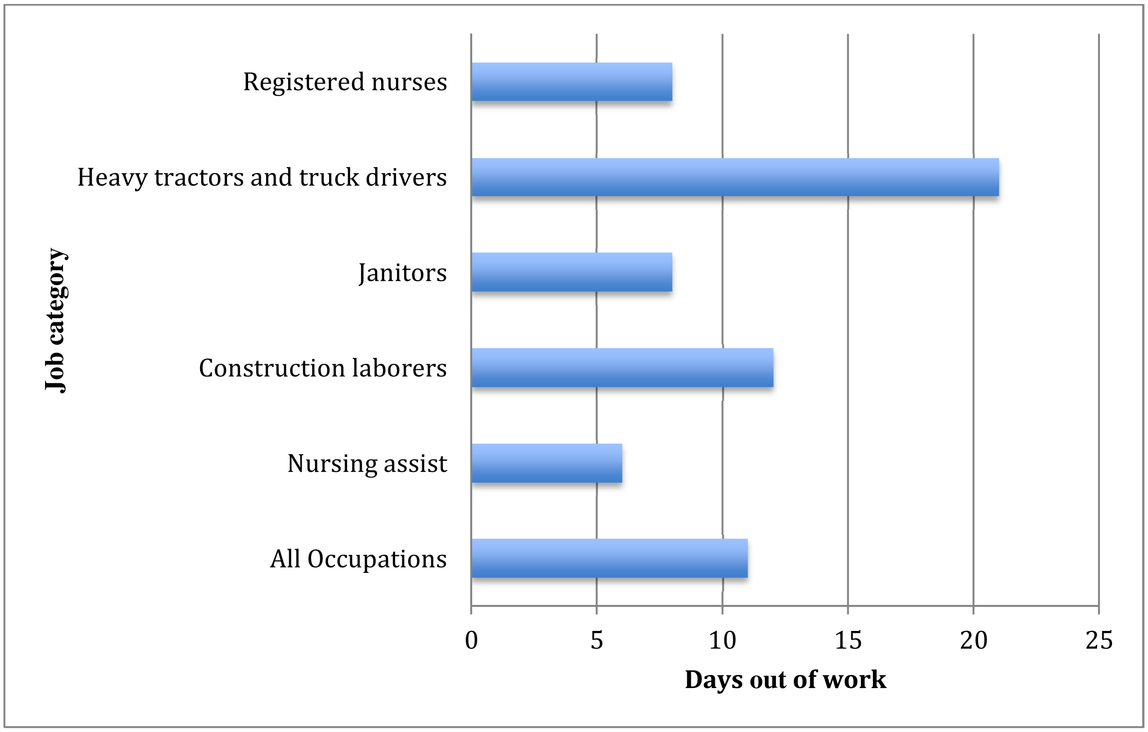

Figure 2- Average days out of work per injury by type of industry (Bureau of Labor Statistics U S Department of Labor, 2012)

More workers are affected by MSDs everyday in the construction field. As a result, workers are leaving the construction workforce earlier. Looking at one (Holmström & Engholm, 2003) study, the Swedish construction work force numbers are shrinking with age, and this shrinkage is not translated through advancement of jobs. This means that the numbers of workers aged 50 years or more is 70% less than workers under 26 years old. Moreover, the decrease in the number of workers 50 years and older is not because most of the workers are promoted to higher jobs; rather, in the same study the numbers report a decrease in young people at the higher jobs also. Thus, workers are leaving the construction workforce, and MSDs can be one of the causes that led those workers out of the work force.

Risk factors and symptoms of MSDs in construction sites

Risk factors are always associated with the tasks that are being performed by workers in any field. In construction, tasks differ by workers' job descriptions such as masonries, electricians, builders, and painters. Each one of these job's holders are performing their tasks in a way that make them more vulnerable to one or more injuries over time. Following is a brief description of each of the risk factors.

Over exertion of force, duration, and posture

It is valid to always assume construction work to be forceful because no task in the construction site could be done without exerting a considerable amount of work with various body postures that might escalate the exposure of risk factor (Alwasel, Elrayes, Abdel-Rahman, & Haas, 2011, 2012; Alwasel, 2011). Carrying heavy loads is not the only form of overexertion that can lead to injury. Overexertion can be carrying light weights while the carrier's body is not in a safe posture. For instance, carrying loads and placing bricks on top of each other is responsible for most injuries among construction workers (Memarian & Mitropoulos, 2012). Masons carry heavy bricks from the ground and place them in their respective places. Depending on where this place is, the amount of force exerted and the worker's posture is determined. This means that, if a mason is at the beginning of building a wall, the usual posture is that the worker is bending towards the ground, and his/her assistant will be standing beside him/her to deliver the bricks. The amount of force exerted by the worker in this posture might exceed the muscle tolerance at any point of time mainly because of the posture and partially because of the force. It has been shown (Dolan, Earley, & Adams, 1994) that increasing the load increased the spinal bending torque and extensor moment steadily, whereas changing the posture when carrying the load between lifting loads while knees are straight and when knees are bent showed an increase in the bending torque by 75% compared to lifting while knees are bent. This increase in bending torque potentially causes the injury. This is because with the increase in the load, the bending torque increases exponentially and without the worker knowing he/she is overexerting the force and developing injury.

Further, construction work is typically performed according to a plan that is prepared by civil engineers. This plan includes a time frame for any task. Engineers tend to not account for rest allowance in their plans. As a result, the worker is expected to complete physically demanding tasks within a predetermined time. Rest allowance is the time needed for the body tissues to regain its normal shape and condition after the removal of force. This time allows the tissue to heal from micro damages due to the application of force.

Furthermore, (Rohmert, 1964) found a relationship between the amount of load on the tissue and the time that tissue can tolerate the load. Beyond this time the tissue starts to develop injuries until the worker perceives the pain at a later stage. For instance, a construction worker trying to mount a window needs to lift the window first and then hold it there for some time in order for his/her assistant to be able to mount it properly. If not the load, the prolonged time that the worker spends holding the window will eventually exceed the tolerance of the tissue, and then an injury happens. Capturing these time, posture, and motion relationships is the objective of a burgeoning area of research and technologies. Those technologies are described in the following section.

State-of-the-art motion capture techniques

The motion capture industry recently is moving in two streams. One stream is video capturing of the subject. An example is the Vicon system. The other stream is inertial measurement units, (IMUs) such as the MVN biomechanics suit from Xsense. The two systems provide the user with accurate motion data. However, the limitation of the two systems are the same: cost, mobility, and processing requirements (Vicon, 2013; Xsense, 2013).

Video capture systems have the benefit of accuracy over other techniques; however, these benefits come with a high cost. To capture three-dimensional data of the moving body with the video technique, the system requires at least 3 cameras that have a direct line-of-sight with the object. This means that the more cameras deployed the more accurate results users will obtain. However, the line-of-sight feature cannot be assured in all work environments, especially construction environments where the implementation of such complicated systems is nearly impossible due to their sensitivity to physical impacts on the scene and the cost of deploying many cameras in order to cover the entire worksite. In addition, the subjects to be tracked with such systems have to wear markers for each point tracked which will be tedious for workers in physically demanding jobs. After obtaining the data from the camera system, a user has to revise the videos frame by frame to account for the missing frames due to loss of line-of-sight or movement artefacts which adds more time to obtain the results making the system not an online application. Thus, videogrammetry is not typically a feasible option to track MSDs risk factors in industrial settings.

It is shown (Ray & Teizer, 2012) that using a range (Kinect™) camera, workers posture can be classified. The identification of a subject's posture was successfully implemented in a non-structured environment. This kind of technology require deploying a camera in every angle of the project to be able to track workers' posture all times to identify MSD risk factors on the field. The cost of deploying cameras in addition to the questioned ability of such systems to analyze two or more workers at the same time makes it non-suitable for worksites in the mean time. Moreover, accelerometers showed the capability to classify workers' posture (Joshua & Varghese, 2011a, 2011b). However, these systems are classifying the worker's posture offline through post processing. Also, accelerometers suffer drift and for continuous monitoring of worker's posture, accelerometer's drift will produce misleading information.

IMUs on the other hand do not cost as much as videogrammetry. They require no line-of-sight, and provide measurement with an accuracy of $<0.05^0$. The IMUs have many advantages over videogrammetery, however, they use the fusion of accelerometer, gyroscopes, and magnetometer data to compensate for the drift of these measurement units. The fusion of these three types of measurement makes it complicated to obtain the final results required (orientation and position). Another problem for the IMUs are their cost, as they require a suit (measurement suit) for each individual. These suits currently cost around 10,000$ CAD. Also, these suits are sensitive to physical impacts that are present in any industrial setting. Also, the measurement of IMU is non-direct, meaning IMUs integrate acceleration to obtain the angular displacement or velocity that makes them prone to drift that affect the results.

A direct measurement technique is required that is able to detect the joints of interest in a non-invasive way. The technique should be easy to use, economically affordable, drift-free, deployable, and robust. These features cannot be achieved using the state-of-the-art techniques reviewed in this section.

Methodology

In this paper, a direct system to track motions of construction workers is presented. The system uses an optical encoder placed non-invasively along the axis of the joint rotation, the knee joint in this case. The optical encoder (Bourns, 2011) is mounted to an exoskeleton which is an off-the-shelf knee brace (Flexlite hinged knee support). The brace as shown in figure 3 has two axes. One is aligned with the thigh and the other is aligned with the shank. The optical encoder is inserted at the intersection of these two axes. This configuration allows the brace to reduce knee motions to a simple hinge joint rotation that follows knee flexion. The optical encoder contains a rotating and a fixed part. The fixed part is rigidly attached to one of the brace arms, while the moving part is fixed to the other arm. Figure 3 shows the brace configuration.

The sensor system is controlled by a PIC18F87J50 microcontroller from Microchip Company. The controller receives the two signals from the encoder and saves them temporarily in the buffer before sending them into an SD card attached to the circuit. The data is stored in the SD card for later uploading. The system runs on a 1000 sample/s acquiring rate that is one order of magnitude higher than commercially available motion capture data. It uses a 9V battery with a voltage regulator to supply the components with 5 and 3 volts.

Data transmission from sensor to the storage unit is performed in two steps, one from sensor to microcontroller the second is from microcontroller to SD card (storage unit). The system includes a mini USB interface that provides the ability interface the PC to the sensor system.

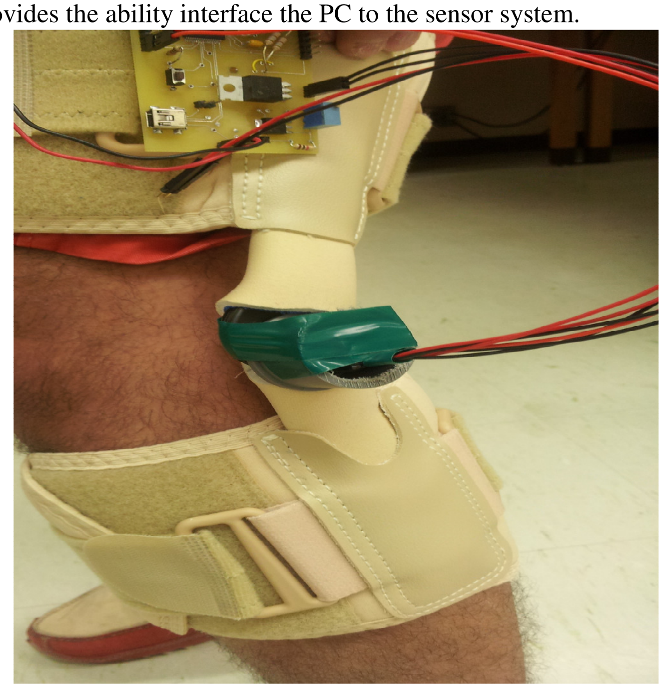

Figure 3- Configuration of the sensor system attached to the knee joint

With the rotation of the knee, the brace arms follow the motion of the shank and thigh. Similarly, the encoder rotates, mimicking knee flexion and yielding a direct measurement of the knee flexion angle. A healthy male graduate student was instrumented with the sensor system and asked to perform a stand-sit-stand sequence repeatedly. Each sequence started with the subject standing erect, sitting, and standing up again.

The sequence was repeated 8 times to study trial-on-trial variation. Between trials, the subject was asked to rest while the operator downloaded the data into a computer. The trials are designed to demonstrate the feasibility of the sensor system as a monitor for the risk factors of MSDs. However on a work or construction site; we plan to add a Wi-Fi transmitter to provide a real-time wireless link to the central computer instead of the current wired link.

RESULTS

This paper aims to show the feasibility of a new technique of measuring human joints' angles in industrial setting. The results reported are a sample of the experiments conducted due to space limitation. The results of three sample trials are presented in figure 4. The results show that the sensor is able to track the knee angle rotation with a resolution of 2.8125^0. The encoder uses a binary output format. It reports angular displacement in discrete steps of 2.8125^0. The results show that the sensor system can differentiate between slow and fast knee flexion patterns. The slope of trial 7 compared to trial 4 shows that the participant bent his knee in trial 7 faster than he did in trial 4. Numerical differentiation of the angular displacement measured by the sensor can be used to obtain angular speed and acceleration. Most importantly time spent in a static posture can be measured.

The subject had a pattern in which he starts with a relatively slow motion passing from 0 to 56 degrees in 5 seconds and then remains constant and travels back to zero position from 56 degrees in 2 seconds. The participant was asked to simulate sitting on a chair as much as possible, and the experiment setup did not include a chair. That is why the participant did not exceed the 60 degrees flexion due to his muscle strength. This pattern of flexing the knee slowly and extending it back quickly means that the participant's flexor muscles started the fatigue phase where muscles cannot provide the force required to maintain the body weight at 60 degrees flexion. Thus, the participant raise fast to an erect position at zero flexion, which requires much less force than the 60 degrees flexion.

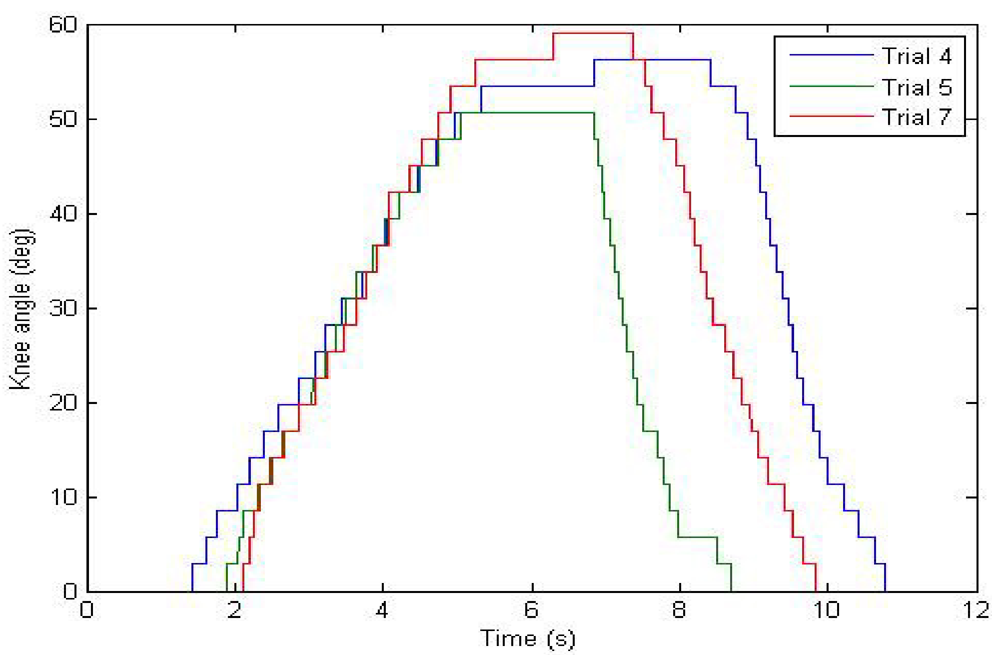

Figure 4- Three stand-sit trials measured using the proposed sensor system

DISCUSSION

Alwasel et al. (2011) showed that measuring human joint angles is enough for identifying MSD threats to workers in construction sites (Alwasel et al., 2011). The joint angle can be used as a stand-alone tool to asses risk factors such as shoulder injury. It also can be integrated with other techniques to provide a full solution for human motion tracking outside specially instrumented settings.

The trials described in this paper showed that the proposed sensor system can track knee flexion with a resolution of 2.81^0 repeatedly with minimal trail-on-trial measurement variation. The sensor resolution is lower than that available using commercially available motion capture techniques. However, the resolution of our sensor depends on the type of encoder used. Commercially available encoders with a better resolution can be used to improve the resolution of our sensor system to sub-degrees.

The sensor system is applicable to any hinge-like joint, such as the elbow, wrist, and foot. A complete tracking system of the human body would require design of the envelope on which the encoders will fit to follow the anatomical joint rotations in order to measure them directly.

CONCLUSIONS

A mobile, cheap, real-time, and drift-free system to track human joint angles is presented. The system eliminates the need for sensing infrastructure. It provides a new sensing scheme to enable the identification of unsafe ergonomic behaviour. That, in turn, should decrease the prevalence of the workplace MSDs over time. In addition, this sensor system can be used to train new employees according to occupational health and safety regulations. It can be configured to either alert the worker in real-time to unsafe postures, thus providing on-the-job ergonomic training and active injury protection, or to accumulate information on types of worker activities performed in order to re-design the activity or to manage worker exposure to cumulative risk factors.

The results indicate that the system is applicable to the knee joint as well as other body joints and can directly measure joint angles without the need for complex mathematical operations. Further testing and redesign is planned to increase the system accuracy in order to obtain sub-degree resolution and application to other joints.

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